

DOCUMENT RESUME

ED 335 007

IR 015 174

AUTHOR Rieber, Lloyd P.
TITLE Computer-Based Microworlds: A Bridge between Constructivism and Direct Instruction.
PUB DATE 91
NOTE 18p.; In: Proceedings of Selected Research Presentations at the Annual Convention of the Association for Educational Communications and Technology; see IR 015 132.
PUB TYPE Speeches/Conference Papers (150)
EDRS PRICE MF01/PC01 Plus Postage.
DESCRIPTORS *Behaviorism; Computer Assisted Instruction; Computer Simulation; Discovery Learning; *Educational Technology; Elementary Education; *Instructional Design; *Learning Theories; Microcomputers; Programed Instruction; Science Instruction; Student Motivation
IDENTIFIERS *Constructivism; Direct Instruction; LOGO Programing Language; *Microworlds

ABSTRACT

The field of instructional technology is characterized by its products, such as instructional media, and its processes, such as instructional design. The process of instructional technology has been shaped by advances in learning and instructional theory over the past 50 years. Much of the development work of the field to date has been on direct instruction, or instruction based largely on the application of behavioral principles. Most computer applications are based on principles of programmed instruction--the computer becoming the ultimate teaching machine. In contrast to behavioral learning, constructivism, a faction within cognitive psychology associated with the application of Piagetian learning theory, is characterized by discovery and experiential learning. Constructivists have sought to tap the computational power of modern microcomputers to create computer "microworlds" where learners can experience and appropriate sophisticated ideas from (but not limited to) the domains of science and mathematics. Probably the most well-known computer applications of constructivism is LOGO. Proponents of constructivism and direct instruction are usually viewed in opposition to one another. It is suggested that computer microworlds offer an immediate compromise between these two camps. In this paper, constructivism and microworlds, as well as related research on mental models, misconceptions in science, and intrinsic motivation are reviewed. Finally, some considerations are offered in the design of microworlds which can be used as an aid to direct instruction. These design considerations are presented in the context of "Space Shuttle Commander," a prototype project developed to teach motion concepts based on compromises between principles of constructivism and direct instruction. (68 references)
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Computer-Based Microworlds: A Bridge Between Constructivism and Direct Instruction

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Abstract

The field of instructional technology is characterized by its products, such as instructional media, and its processes, such as instructional design. The process of instructional technology has been shaped by advances in learning and instructional theory over the past 50 years. Much of the development work of the field to date has been direct instruction, or instruction based largely on the application of behavioral principles. Most computer applications are based on principles of programmed instruction — the computer becoming the ultimate teaching machine. In contrast to behavioral learning, constructivism, a faction within cognitive psychology associated with the application of Piagetian learning theory, is characterized by discovery and experiential learning. Constructivists have sought to tap the computational power of modern microcomputers to create computer "microworlds" where learners can experience and appropriate sophisticated ideas from (but not limited to) the domains of science and mathematics. Probably the most well-known computer application of constructivism is LOGO. Proponents of constructivism and direct instruction are usually viewed in opposition to one another. It is suggested that computer microworlds offer an immediate compromise between these two camps. In this paper, constructivism and microworlds, as well as related research on mental models, misconceptions in science, and intrinsic motivation are reviewed. Finally, some considerations are offered in the design of microworlds which can be used as an aid to direct instruction. These design considerations are presented in the context of Space Shuttle Commander, a prototype project developed to teach motion concepts based on compromises between principles of constructivism and direct instruction.

Instructional technology can be defined as the application of what is known about learning and teaching on current instructional practices (Knirk & Gustafson, 1986). Instructional technology is by its very nature a practical concern and instructional technolo-

gists are essentially educational pragmatists. All share the mission of applying whatever knowledge bases are available to achieve "the goals" of the instructional system. Interestingly, instructional technology is often equated with one of many instructional media or models of instructional design such as those based on the instructional systems development (ISD) approach, but these are mere instances of instructional technology which do not cover its breadth of scope and purpose any more than addition or subtraction defines mathematics or engineering. Instructional technology is an evolving and dynamic field which is naturally susceptible to the tension between the many internal forces and perspectives, both current and historical, which seek to define it.

Learning theory is arguably the most significant foundation of instructional technology (Gagné & Glaser, 1987). Advances in learning theory have had considerable influence on instructional technology. Instructional technology, in its modern form, began as an attempt to apply behavioral learning principles to instruction and quickly merged with the audio-visual movement of the middle 1900's (see Reiser, 1987, for a historical review). Instructional technology has since proceeded to a neo-behavioral philosophy (Case & Bereiter, 1984) which considers the learner as a more active agent in the learning process. Most applications of computer-based learning have been extensions of the programmed instruction paradigm as set forth by Skinner (1968). The pioneering work of Patrick Suppes in the development of computer assisted instruction (CAI) in arithmetic is a prime example (Suppes & Morningstar, 1972). Cognitive psychology has become a major influence on instructional technology over the last 15 years, though probably more conceptually in the writings of the field than in actual practice (Gagné & Dick, 1983; Hannafin & Rieber, 1989; Shuell, 1986).

The ISD approach to instructional design has characterized much of instructional technology since World War II (Knirk & Gustafson, 1986). While many people still equate ISD with behavioral learning, it is

argued that this presents too narrow a definition of current applications of ISD. Many ISD approaches and methods have tried to blend behaviorism and cognitivism in order to achieve learner-centered instruction which is still goal-oriented. Many are based on accretion or reception learning models where meaningful learning is seen as a progression through a series of stages along a novice to expert continuum (Ausubel, 1968; Norman, 1982; Mayer, 1984) or on a hierarchy from lower-level learning to higher-level learning (eg. Gagné, 1985). Expert status is achieved through a process where knowledge is successively acquired and organized, and then integrated or "fine tuned" into existing knowledge structures. One might label this approach to instructional technology as "instructivism" because the instructional goals are still the dominant influence on instructional design, despite the concern and care given to learner abilities and needs.

Among the achievements of cognitive psychology, the writings of Jean Piaget remain an important watershed. Though his work has been extended and more fully elaborated, Piaget's basic model of human learning and development remains intact. Piaget's work, though popular and influential in Europe for decades, was not embraced in this country until about 1970, having been overshadowed by the behaviorist movement until that time. Recent applications of Piaget's work over the last ten years are usually grouped under the heading of "constructivism." Interestingly, the influence of constructivism has only recently begun to spill over to the field of instructional technology. Probably the most well known computer-based application of constructivism is LOGO, a computer language designed to reflect and promote Piagetian learning. LOGO was the result of a collaborative effort between the Massachusetts Institute of Technology (MIT) and Bolt, Beranek, and Newman (BBN), and was initially funded by the National Science Foundation. Though LOGO involved the contributions of many people, such as Wally Feurzeig, Daniel Bobrow, Hal Abelson, and Andy diSessa, Seymour Papert is usually credited as LOGO's chief developer. LOGO is a primary example of an application of constructivism based on "microworlds." A microworld, as the name suggests, is a small, but complete subset of reality in which one can go to learn about a specific domain through personal discovery and exploration (Dede, 1987; Papert, 1981).

The major premise of this paper is that instructional technology in general, and educational computing in particular, need to seriously consider the infusion of constructivism into instructional design and that microworlds represent an immediate application. Mi-

croworlds can offer goal-oriented learning environments in which learning is achieved through activities which promote discovery and exploration. The compromise is reached largely through a *guided-discovery* orientation to learning where the nature of the learning activity and experience is naturally constrained by the parameters imposed by a particular microworld. Microworlds offer a compromise between the strict deductive approach suggested by ISD models and pure inductive learning advocated by experiential learning theorists. However, because the microworld's boundaries are severely limited, the range of learning outcomes is also constrained making the achievement of predetermined learning objectives possible and probable, which is the aim of instructivism.

In this paper, the constructivist position on learning based on several milestones of Piaget's theories will be summarized and applied to computer microworlds. Also reviewed will be two important areas which have a direct bearing on the design of microworlds for specific goals: intrinsic motivation and mental models. Intrinsic motivation is one of the important assumptions of the constructivist approach, but yet is rarely described in detail by its advocates. Mental models comprise an important area of research in cognitive psychology. Mental model research is helpful in understanding human knowledge about the world and subsequent human interaction within it. Most of the microworlds created thus far, like most of the mental model research conducted to date, have been in technical areas, such as physics and mathematics. Insights gained by mental model research closely parallels the goals of microworld design. Finally, a series of design principles will be presented which attempt to synthesize the collaboration of instructivism and constructivism. An original computer-based development project will be used in the presentation of these principles.

Constructivism

Constructivism is the name of a school of educational philosophy closely aligned with the theories of Jean Piaget (see Forman & Pufall, 1988a, for a review). At the heart of constructivism is the idea that learning involves individual constructions of knowledge. Constructivist proponents range from those who stress a strong humanistic orientation where learning occurs through open discovery (eg. Rogers, 1969) to those who accept the imposition of varying degrees of structure depending on the setting (eg. Howe, O'Shea, & Plane, 1980). Constructivists describe learning as occurring through interactions with one's environment or "culture." Therefore, the potential for learning at different levels is thought to grow as the environ-

ment becomes richer and more engaging. Computer enthusiasts, such as Papert (1980), feel that the computer offers a powerful medium for the exploration and discovery for many ideas, particularly in science and mathematics, just as a young child might explore the concepts of volume given a sandbox and mass and momentum given a bag of marbles.

Piaget's theory of cognitive development essentially has two parts: stage dependent and stage independent (Mayer, 1983). Most of the attention to Piaget's theory is usually given to the stage dependent part, or that which refers to the four stages of development that people presumably progress through: sensorimotor, preoperational, concrete operations, and formal operations. However, Piaget's stage independent theory is of most interest in the design of computer microworlds. It concerns two processes: the *adaptation* of an individual to survive and flourish in an ever changing environment; and the need for *organization*, or stability and coherence of the world knowledge and experiences learned "to date." Piaget referred to this organized set of knowledge and understanding as internal structures or schemata. The processes of adaptation and organization create an intrinsic conflict which provides the platform for lifelong learning. The goals of one process are in contrast to the goals of the other. Life entails a continual balancing between the two which is accomplished through the process of *equilibration*. *Assimilation* and *accommodation* are the two well-known mechanisms which carry out the process of equilibration. Assimilation subsumes new information under an already understood structure or schemata. A baby who has learned to throw a tennis ball is also likely to throw a rubber ball as well as an orange. Both the rubber ball and the orange fit the structure that one "throws round objects." Accommodation builds new structures from old structures when incoming new information no longer fits an existing structure. The baby soon learns to accommodate the fact that some round objects are to be thrown, and others are to be eaten.

Assimilation and accommodation result from the natural conflict which occurs through everyday encounters with the environment. Learning can only occur when an individual is in a state of disequilibrium, or cognitive conflict. Given new information, an individually intrinsically seeks to assimilate, or incorporate, the information into preexisting structures. Accommodation is triggered when new information no longer fits established structures, necessitating the adaption of new structures.

Constructivism, the instructional application of Piaget's work, consists of three properties: epistemic conflict, self-reflection, and self-regulation (Forman

& Pufall, 1988b). Epistemic conflict is the Piagetian process of equilibration. Learning occurs when the environment presents a problem which is outside of the individual's repertoire but which the individual still seeks to resolve. Even though the conflict may be induced by some external agent, such as a teacher, resolution is achieved only by the individual. Each resolution is an individual construction. Self-reflection involves an individual's attempt at objectively and explicitly representing reality and is a response to conflict. Self-regulation is the spontaneous restructuring of thought which is embodied in the Piagetian process of accommodation and assimilation. Old mental structures are refined to be more comprehensive as well as new structures formed. Conflict and reflection are necessarily prerequisite to self-regulation.

Proponents of constructivism emphasize the quality of knowledge structures over their quantity. Learning is viewed not so much as the acquisition of knowledge, but as the constant reconstruction of what is already known. Individuals do not simply add information to their knowledge "banks," but either revise existing mental structures to accept new information or formulate new structures based on old ones when an existing structure is no longer sufficient. As Forman and Pufall (1988b) note: "Central to constructivism is the assumption that to know is to continually reconstruct, to move from a more to a less intuitive state" (p. 240).

One of the most promising attempts at creating computer environments which foster the construction (assimilation and accommodation) of knowledge are microworlds. Microworlds offer instructional designers two key advantages. First, microworlds present learners with experiences *within* specific boundaries of a domain. Second, microworlds offer learners with "stepping stones" *between* interconnected ideas within the domain by allowing rudimentary ideas to first become established and then transformed into more sophisticated aspects of the domain.

Computer Microworlds

A microworld is small, but complete, subset of a specific environment or domain. Microworlds are often confused with simulations. Characteristics of the two can heavily overlap or even be synonymous as well as remain entirely distinct, depending on their design and most importantly on how they are used in a learning interaction. A microworld has two essential characteristics which might help make this point more clear. First, a microworld embodies the simplest model of a domain that is deemed accurate and appropriate by an expert. Second, it offers an initial point of

entry which matches the user's cognitive state to allow fruitful interactions to take place. For example, Cuisenaire rods act as a microworld for many mathematical ideas. They embody the manipulation of a set of introductory mathematical ideas which are valid from any mathematician's point of view, but function at the level of the children who use them. Cuisenaire rods offer not a mathematical simulation, but permit *real* mathematics to take place. On the other hand, simulations can be designed which do not offer any significant difference from real-life experiences, such as the sophisticated flight simulators used for training by the military and most major airlines. These simulations would not be considered microworlds for most people because they are designed to represent as many of the variables and factors of the real experience as possible. It is important to remember that microworlds, like simulations, do not have to be computer generated. However, the computational and graphical power of computers provide a powerful arsenal to microworld designers.

Simulations can become microworlds with design changes. A computer flight simulation can easily be designed to permit manipulation and experience with only one part of the aircraft, such as the rudder. In this sense, the simulation becomes a "rudder microworld." Similarly, many microworlds can easily become simulations. Consider a mathematical microworld which involves the estimation of distances such as by using the LOGO command FORWARD to move the turtle from one point to another on the screen with as few commands as possible. This microworld becomes a "whale search" simulation simply by changing the turtle into an animated "boat" and the screen target into a "whale." The mathematical microworld has not changed, only the context.

Papert (1980) suggests that microworlds, like all powerful ideas, should fulfill four criteria. They should be simple, general, useful, and syntonetic. Syntonetic learning means "it goes together with." Syntonetic learning suggests that learning is made up of connections, such as connecting new ideas to old. Syntonetic learning means going from the "known to the unknown" which is central to every idea in cognitive psychology. These learning connections are enhanced in a microworld through learner control. This is in contrast to research on learner control of direct instruction which frequently suggests that learners are often poor judges of their own learning paths (Clark, 1980; Steinberg, 1977).

Microworlds rely on the natural tendency of a learner to seek equilibrium. Successful microworlds actually encourage learning conflicts to arise in order to activate the process of equilibration. It is only

through the resolution of these conflicts that learning can take place. The trick is to structure the microworld so that the learner has an environment in which conflict resolution is within their grasp. Microworlds offer learners with the opportunity to exercise a cognitive or intellectual skill which they would be unable or unlikely to do so on their own either because there is no intrinsic reason to do so or because no sufficient tool is available with which to allow the learner to construct the experience.

Creating "Objects to Think With"

LOGO represents the most ambitious attempt to date at creating computer-based microworlds in which learners have ready access to mathematical ideas and heuristic problem-solving. Another is BOXER, a computer-based microworld which combines computational and text-processing tools in a programming environment based on interacting windows called "boxes" (diSessa & Abelson, 1986). Whereas BOXER is still under development and is not yet available for general application, LOGO has had widespread dissemination on most microcomputers over the last 12 years. Turtle geometry is one such LOGO microworld which gives learners access to geometric principles through interactive graphics. The LOGO turtle is a cybernetic animal that "lives" on the computer screen and follows a set of commands like forward, back, right, and left. As students "drive" the turtle around the screen it leaves a trail, thus allowing students to create graphics through the manipulation of mathematics (see Abelson & diSessa, 1981; Lockard, Abrams, & Many, 1990; and Lukas & Lukas, 1986, for further descriptions and discussions of turtle geometry). Research on LOGO is inconclusive (see review by Clements, 1985), perhaps because, as Papert (1987) contends, LOGO is meant to be part of a cultural influence on learning and considering its effects on learning in isolation is not defensible. The issue here is not the success of LOGO but the way in which LOGO was developed to achieve constructivist goals.

Successful LOGO learning experiences are founded on many key ideas, many associated with programming. For example, LOGO is procedural, which encourages "top-down" problem-solving in which a large problem can be broken down into smaller, more manageable "chunks." However, the turtle embodies the essence of constructivism by being an "object to think with" (Papert, 1980). Papert (1988) goes so far as to suggest that the turtle may represent a "mother structure" for differential geometry. Mother structures are the most fundamental ideas or concepts upon which cognition is built.

At the heart of constructivism is a search for good

objects to think with. Almost anything can become a good object to think with: pots, pans, mudpies, blocks, legos, etc. Some are more flexible and generalizable to a variety of domains than others. Meaningful interaction with objects in the environment liberates and encourages the equilibrium process. The turtle is but one example of an object to think with that is made possible by computer technology. Papert contends that the computational power of the turtle makes certain ideas from the world of mathematics and problem-solving accessible to children that previously were considered as too "formal" or abstract to be understood. Several characteristics of the turtle in particular help make this possible: the turtle as a transitional object; and the turtle as an aid to "debugging."

Young children often begin using LOGO for self-guided learning within minutes of encountering the turtle. This is largely achieved by the role of the turtle as a transitional object between themselves and the computer. The turtle is body syntonic with a child in that both share two important characteristics: a position and a heading. This simple fact has powerful consequences. From the start, even a young child has something in common with the turtle. This commonality immediately provides the bridge to new ideas. Young children quickly anthropomorphize the turtle creating an ego syntonic relationship with the turtle. This encourages the Piagetian concept of decentering in which young children begin to see the world from several perspectives. The anthropomorphization of the turtle also encourages the articulation and communication of mathematical ideas. Children begin to acquire the "vocabulary" of turtle geometry through their communications with the turtle. Since the language of the turtle is LOGO and the language of LOGO is mathematics, children have a way in which to verbalize mathematics.

The second important characteristic of the turtle is as an aid to "debugging" which is the identification and correction of errors within a computer program. In most forms of instruction errors are something to be avoided: errors imply failure. In LOGO and constructivism, errors are a natural consequence of interactions. Errors, instead of having negative connotations, are useful so long as they provide a rich source of information for subsequent interactions. Errors are a natural part of all human endeavors. The informational feedback that errors provide is very potent especially when a learner has a strong commitment to the action that triggered the error (eg. Kulhavy, 1977). Error detection is made intuitively obvious in LOGO with the turtle's role as a graphical tool. The turtle's animated graphics provide almost instantaneous

graphic feedback to a learner. This rapid turn-over of learner action and feedback encourages risk taking and hypothesis testing. The forming and testing of hypotheses through graphical feedback becomes more important as a learner's computer program becomes more complex.

Mental Models

Daily activities require all of us to interact with a complex environment. Many researchers and theorists suggest that people form mental models of the physical world and the objects and activities within it (see Gentner & Stevens, 1983, for a review). A mental model is an individual's conceptualization of a specific domain or "system." Students develop and use mental models to help explain and solve general classes of problems. Far from formal and static entities, mental models are loosely organized and forever changing as new interactions with the environment suggest adaptations. Mental model research has concentrated on technical domains, like physics or electricity, because they are far more normative and are more easily made explicit than most other domains, such as "parenting." Although researchers may use highly specific domains, theorists suggest that people form mental models of a large number of systems ranging from the kitchen stove to Newtonian mechanics (see Norman, 1988, for a discussion of ways in which people form mental models of everyday things).

Mental models serve explanatory and predictive purposes. Survival demands that we be able to predict everyday events with a high degree of success. The routine need to cross a street is a prime example. Beyond all of the perceptual requirements (such as estimating the width of the street and the speed of oncoming cars) is a need to understand the many "street" systems which operate together. Just a few of these systems include the workings of an automobile, traffic lights, and physics. Our understanding of each of these systems is crucial as we decide when is an appropriate time to cross the street as well as if we can casually stroll across or should attempt an "Olympic sprint." Any misunderstanding of one of these systems could be as deadly as any misjudgment of distance or speed. For example, consider your mental model of an electric "Walk" sign at an intersection and what it means when it begins to flash. Can you still initiate the crossing? What should those already part way across do? Each interpretation can have dramatically different consequences. Mental models of everyday things usually form through interactions with the environment. However some systems, such as the physical sciences, are difficult to understand through a wide range of random interactions. Microworlds offer a

platform for appropriate conceptualizations of such systems to form and develop.

The application of mental models to the instructional design of microworlds involves the consideration of three things: the target system, the conceptual model of that target system, and the user's mental model of the target system (Norman, 1983). The target system is the actual system that a learner is trying to understand. For example, Newtonian mechanics or thermodynamics are typical target systems. A user's mental model describes that individual's conception of the target system; a person describes how the target system works and predicts its behavior based on their mental model of the target system. A user's mental model may or may not be an accurate reflection of the target system. For example, research has shown that many people hold a mental model of motion problems based on Aristotelian rather than Newtonian principles (Champagne, Klopfer, & Anderson, 1980; diSessa, 1982). Hence, many students reckon that a ball comes to a stop soon after being thrown because it "runs out" of force. A conceptual model is presented to a learner as an aid to understanding the target system. Conceptual models are usually invented by teachers, designers, or engineers.

For all practical purposes, a microworld is largely synonymous with an *interactive* conceptual model. It embodies the simplest working model of a system in which an individual can begin to understand the target system. A conceptual model can often be metaphorical to the target system, such as suggesting that the flow of electrons in a wire is "like water running through a pipe." In such cases conceptual models, like microworlds, offer a temporary "doorway" to a set of larger ideas. For example, Papert (1980) has recounted the way in which his fascination with gears as a young boy offered him with a beginning conceptual model of mathematical ratios and proportions. For Papert, gears became a personal microworld which helped concretize many abstract mathematical ideas for him. This does not imply that the gears metaphor should be introduced into the mathematics curriculum, but instead suggests how a microworld can provide an introductory conceptual transition into a learning domain.

Even as adults, we all have and form mental models of everyday objects and events, such as kitchen stoves, bathroom shower controls, and light switch panels (Norman, 1988). A particularly good example is the thermostat of a home furnace. Many people believe that the higher you set the thermostat, the faster your home gets heated, when in reality this is not the case. A personal example concerns an old black and white television set I have in my bedroom. When I turn on

the set, its power quickly goes on and then off. If I tap the set, it will quickly turn on and off again. In order to get the set to turn on and stay on, I have to carefully tap the set until the "connection catches." I have learned that there are better places to tap the set than others. I have become particularly adept at how to turn the set on, and I frequently coach my wife and daughter on the "technique." Now, I know nothing about television repair or about electrical devices, yet I have developed my own "loose connection" theory, or mental model, to define the set's electrical problem (assuming it is an electrical problem). I formed and tested many hypotheses until finally arriving at the one I feel is accurate. It is important to note that this was done informally and naturally. So far, this mental model allows me to predict future instances of the set's performance and thereby governs my actions.

Mental model research is closely aligned with research on misconceptions in science (Eylon & Linn, 1988). Misconceptions in science have been documented in many specific domains, from physics and optics to mathematics and biology. Misconceptions about the laws of motion have been a favorite domain of study. Research has shown that students form strong personal theories, though naive, about the physical world which are based on intuitive, and frequently inaccurate, models (Champagne, Klopfer, & Anderson, 1980). For example, it is commonly viewed that students tend to hold an incorrect Aristotelian model of the physical world. Some proponents of this view, most notably McCloskey (1983), suggest that the instructional course of action is to force a theory change in students: from an Aristotelian theory to a Newtonian one, for example. This is accomplished by placing students in situations where they are confronted by evidence which conflicts their personal theories, thus exposing the falsehoods of their intuitive assumptions. Others, such as diSessa (1988), propose that students do not have any "theory" in any sense of the word, but rather claim ownership to a collection of knowledge fragments, some of which are seen by experts as "correct" and "useful" and others as "incorrect" and "detrimental." In contrast, the instructional approach here is to capitalize and build on the student's knowledge base in order to build "a new and deeper systematicity" (diSessa, 1988, p. 51) where old knowledge is traded for new while a mental framework or model is constructed. In either case, problem-solving will be influenced by a student's mental model of the task or domain. Without an established and explicit mental model, students are likely to revert to misconceptions when solving novel problems, even though they may demonstrate mastery of specifically learned facts or procedures when tested.

Intrinsic Motivation

Constructivists make the assumption that learners must find an activity, within a microworld or otherwise, intrinsically motivating in order for the process of equilibration to occur. Lawler (1982) has suggested that microworlds, like those presented in LOGO, are successful because they produce "neat phenomena," or "phenomena that are inherently interesting to observe and interact with" (p. 141). However, constructivists offer little guidance on this issue to designers of microworlds. Turtle geometry, for example, may capture an innate human interest in the visual appeal of graphics, although this is totally speculative.

What motivates an individual to initiate and complete a task? A strict behaviorist would derive this empirically by trying a variety of reinforcements and observing which best sustains the desired response. School environments typically use a variety of reinforcements, such as praise, rewards, and grades. All of these are examples of extrinsic motivators, in that an activity is engaged in order to get the promised incentive, whether it be a star pasted to a school paper, or a good grade on a report card. We all need extrinsic motivators, such as a paycheck, at times in order to get an important job done which we may otherwise not choose to complete.

In contrast, people tend to complete other tasks without the promise of a reward. These tasks or activities have their own inherent appeal and people do not need coaxing to participate. Typical examples include leisure activities such as reading, playing cards, cooking, or crafts. In each of these cases, participation in the activity itself is reward enough. Such activities are intrinsically motivating in that the nature of the activity or domain itself produces significant reason to participate and external reinforcement or pressure to participate is not required (Kinzie & Sullivan, 1989; Maehr, 1976). Of course, an activity which is intrinsically motivating to one person may require extrinsic motivators for another.

Instruction which is intrinsically motivating relies on incentives which are student-centered, rather than external lesson reinforcement. In fact, the addition of extrinsic incentives, such as grades or other rewards, can often undermine or destroy the intrinsic appeal of many activities for students, and, in effect, turn "play into work" (Condry, 1977; Greene & Lepper, 1974; Lepper, Greene, & Nisbett, 1973). Malone (1981) has suggested a framework of intrinsically motivating instruction based on *challenge*, *curiosity*, and *fantasy*. Malone's discussion is particularly relevant here because he has specifically applied this framework to the design of computer games which often share characteristics of microworlds.

Challenge in an activity can usually be induced by establishing goals which have uncertain outcomes. The goal should be personally meaningful to the learner such that the skills or knowledge being learned are viewed as important because they help to achieve the goals. Tasks need to be designed to be optimally challenging, such that they are not too easy or too difficult. But perhaps most importantly, the tasks should elicit feelings of competence, or self-efficacy, in solving problems which students perceive as relevant and important. This enhances one's self-concept and leads to a feeling of control over one's own success (Weiner, 1979).

Closely related to challenge is curiosity. A person's curiosity is usually piqued when an activity is viewed as novel or moderately complex. In addition, curiosity is also usually increased by activities which offer a certain level of surprise. This occurs when the expected and actual outcome of an activity are different or incongruent, a phenomenon which Berlyne (1965) has termed "conceptual conflict." Again, however, both challenge and curiosity produced by a conceptual conflict must be optimally maintained to be effective. A task which is perceived as too easy quickly loses appeal, and a task which is seen as too demanding is avoided. Likewise, a conceptual conflict between expected and actual task outcomes can make a learner seek to resolve the conflict but can quickly lead to frustration if the conflict is too confusing or bewildering. Norman (1978) has termed optimal levels of conceptual conflict as "critical confusion."

Fantasy entails providing learners with a meaningful context for learning which is easy to augment with their imaginations. It is meaningful in the sense that it offers a very personal degree of fascination and intrigue which is easily transferred to play activities. Fantasy educes mental images of a context in which a learner is not actually present. The use of fantasy is common in theme parks and children's films and television programs. Malone (1981) has termed instruction which uses fantasies in this way as *intrinsic fantasies* because the skills to be learned are integral with the fantasy, such as learning about latitude and longitude in order to locate a "pirate's sunken treasure."

These characteristics of intrinsic motivation are all similar to Keller's (1983) synthesis of affective attributes which form the basis of his ARCS (Attention, Relevancy, Confidence, and Satisfaction) model of motivational instructional design. The degree to which these determinants are present in instruction and how they relate to differences in learning are not clear. Some examples of differences in learning given instruction which does or does not provide intrinsic

incentives are the intensity of a learner's arousal and attention to a task, the depth of involvement, and task persistence (Lepper, 1985). Each of these in turn would influence the amount of time learners actually spend on-task and also the level at which mental processing occurs (Maehr, 1976; Malone, 1981; Rotter, 1954).

An Example of Merging Constructivism and Direct Instruction

Although many of the principles of constructivism offer promise in the development of successful learning environments, practical applications are difficult to draw out given the typical constraints of most school and training situations. The purpose of this final section is to synthesize the principles discussed so far by presenting a working prototype of an instructional development project based on the merger of constructivism and direct instruction. This project was founded on compromises between the extreme views of both camps such as accepting the constructivist philosophy that learners should be given rich and powerful environments to build and transform mental structures while maintaining the practicality of current educational conditions which the instructivist position supports. Table 1 summarizes a series of design considerations which are the foundation of this synthesis.

The project involved the development of a computer software package called *Space Shuttle Commander* (SSC). SSC is a "mini-course" which teaches Newton's laws of motion to elementary and middle school students to achieve the learning objectives listed in Table 2. SSC combines the use of computer tutorials and microworlds. The microworlds comprise a series of simulations/games called "missions" in which students pilot an animated "shuttle," as represented in Figure 1. The tutorials consist of a series of "flight lessons" which formally introduce the laws of motion. SSC takes a nonmathematical approach and instead concentrates on concept formation. Portions of both the tutorials and microworld activities in SSC have been validated through a series of ongoing studies involving the role of computer graphics in learning from animated lesson presentations and visually-based simulations (Rieber, 1990a; Rieber, in press; Rieber, Boyce, & Alkindi, in press).

SSC is a direct application of a physics microworld designed by Andy diSessa (1982) using LOGO which involves a dynamic turtle, or "dynaturtle." The dynaturtle is familiar to the turtle described earlier, except that it has one additional characteristic — velocity. The dynaturtle acts as a free-floating Newtonian particle where students can explore motion principles

Table 1
Some Considerations in the Design of Computer-Based Microworlds to Support Direct Instruction

- Provide a meaningful learning context which supports intrinsically motivating and self-regulated learning.
- Establish a pattern where the learner goes from the "known to the unknown."
- Provide a balance between deductive and inductive learning.
- Emphasize the usefulness of errors.
- Anticipate and nurture incidental learning.

in a simulated frictionless, gravity-free environment. Examples of other projects based on the dynaturtle microworld include White (1984) and White and Horwitz (1987). SSC is distributed through the fifteen NASA Teacher Resource Centers located nationwide (Rieber, 1991).

SSC attempts to take advantage of the strengths of tutorials and simulations (microworlds) while minimizing their weaknesses by combining them in a cohesive, yet flexible, course. For example, traditional tutorials, combined with drill and practice, while good at presenting content matter in a logical order and providing practice, are usually monotonous and unimaginative and usually only promote learning at surface levels. Microworlds, presented in the context of simulations and games, offer the potential for intrinsically motivating and cognitively rewarding activities, however, they make the presentation and validation of a predetermined set of learning objectives difficult.

Each of the design considerations in Table 1 will be discussed in the context of SSC.

Provide a meaningful learning context which supports intrinsically motivating and self-regulated learning. The success of any microworld depends on a context in which "neat phenomena" are produced. As the motivation literature suggests, the design of activities in which learners demonstrate commitment and perseverance in the thoughtful completion of a task depends on the degree to which the activity is

Table 2

Lesson objectives for Space Shuttle Commander (SSC)

Terminal Objectives. At the end of SSC, each student will be able to:

- list Newton's three laws of motions;
- apply Newton's three laws of motions given a variety of gravity-free/frictionless situations in one- and two-dimensional space using questioning and simulation techniques;
- state examples and nonexamples of forces;
- describe and explain verbally the functions and control of the simulated space shuttle using vocabulary and concepts from Newtonian mechanics.
- choose to return to the various shuttle missions given the freedom of choice.

Enabling Objectives. The following enabling objectives describe the expected learning outcomes for the flight lessons and the first four missions.

At the end of Flight Lesson 1 and Mission 1, each student will be able to:

- state and apply Newton's first law given the context of no gravity and no friction (an object in motion will remain in motion and an object at rest will remain at rest).

At the end of Flight Lesson 2 and Mission 2, the student will be able to:

- apply an application of Newton's second law where, in one-dimensional space, when an object at rest is put into motion by a force, an equal force must be applied in the opposite direction to stop the object, given the context of no gravity and no friction.

At the end of Flight Lesson 3 and Mission 3, each student will be able to:

- apply an application of Newton's second law where, in one-dimensional space, when unequal forces act on an object in opposite directions, the final speed and trajectory of the object is the result of the difference between the sum of the opposing forces, given the context of no gravity and no friction;
- apply an application of Newton's second law where, in one-dimensional space, the initial acceleration of an object depends on the acting force and the mass of the object, given the context of no gravity and no friction.

At the end of Flight Lesson 4 and Mission 4, each student will be able to:

- apply the principle that, in two-dimensional space, when forces acting on an object occur at right angles to one another they act independently on the object, given the context of no gravity and no friction.

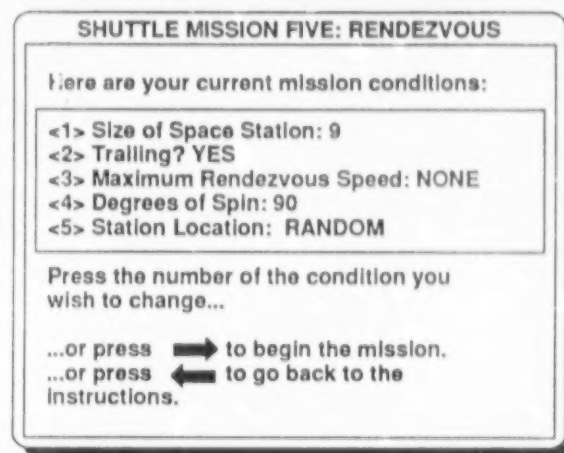
At the end of Flight Lesson 5, each student will be able to:

- state Newton's third law and give at least one example of its application.

FIGURE 1. A representation of the computer screen during an episode of "Mission 5: Rendezvous." The animated "shuttle" is under student control. Arrow keys rotate the shuttle in 90 degree increments and the space bar gives the shuttle a "kick" or thrust in the direction it is pointing. The goal of this mission is to maneuver the shuttle to the space station.



FIGURE 2. Sample screen showing the various mission "conditions" of Rendezvous which can be changed to increase the difficulty and challenge of the lesson. (Not drawn to scale.)



perceived as relevant and its completion as personally satisfying (Keller & Suzuki, 1988). By definition, a meaningful learning context is an intensely personal affair. The goal in education, however, is to discover contexts which have a wide appeal to learners of varying interests and aptitudes. LOGO, for example, seems to attract the attention of children through the use of interactive computer graphics to produce interesting visual designs.

My experience has shown that imagining to be an astronaut appears to be a common fantasy in which children and adults often indulge. The successes and failures of the world's space flights during the past 30 years offer an intriguing context for people's imaginations to go on fantastic voyages in outer space. Beyond all of the fantasy is the very real practicality and necessity of working in space which is continually documented in the media. SSC tries to capitalize on all this by encouraging students to fantasize about being the commander of the space shuttle. The

purpose of the "missions" is to induce and encourage the fantasy in a series of structured activities, each building on the other. The flight lessons are meant to represent "flight school." A similar example of using a meaningful context for learning is the *Voyage of the Mimi*, a math and science curriculum set in the context of whale exploration.

An important conclusion of Malone's (1981) research is that students need to be provided with the ability to continually increase the challenge of an activity in order to maintain intrinsic appeal. Missions 5 and 6, for example, provide students with the opportunity to vary the "mission conditions" (such as target size, target location, shuttle rotation, and other game constraints) in order to increase the difficulty of the activity, such as shown in Figure 2. For example, it is much simpler to control the shuttle in a mission occurring in two-dimensional space when the shuttle's rotation is constrained to 90 degree increments. Control of the shuttle becomes considerably

more difficult and complex when control is changed to 45 or 30 degree increments. In addition, scorekeeping features are provided to allow students to chart their progress under any given set of conditions. Scorekeeping is another feature noted by Malone (1981) as increasing intrinsic appeal in computer games.

Establish a pattern where the learner goes from the "known to the unknown." Meaningfulness can also be interpreted as the degree to which students can link new ideas to prior knowledge, or what the student already knows. The degree to which information is related to prior knowledge is among the most important determinants of learning (Ausubel, 1968). Bruner (1966), for example, suggests a "spiral" approach to learning where the simplest and most general ideas are introduced first to learners in highly interactive and concrete ways. These ideas are then successively reintroduced to students to provide increasing levels of detail. This is similar to Ausubel's (1968) *progressive differentiation*, and Reigeluth's elaboration theory (Reigeluth & Stein, 1983), where general ideas grasped early by learners help them to subsume more detailed ideas introduced later.

SSC can act as an important bridge between experiential learning with a dynaturtle and formal physics (as usually taught in schools). Paradoxically, traditional physics instruction based on highly mathematical models usually removes the influences of friction and gravity in order to "simplify" learning for students. While mathematical formulas may be simplified using this convenience, students' conceptual understanding is usually muddled since the removal of friction and gravity is totally outside of their daily experiences. SSC tries to provide students with a sound conceptual understanding of Newtonian principles to act as "anchoring posts" for subsequent instruction.

In addition, the simulated space shuttle, like its cousin the dynaturtle, acts as a transitional object between the learner and Newtonian physics allowing the exploration of physics ideas within a context that is relevant and fantasy-driven as well as body syntonic.

Provide a balance between deductive and inductive learning. Historically, ISD approaches are based on deductive learning models where the instructional goal is to identify as precisely as possible a set of learning objectives and bring the learner to mastery of those objectives as directly and efficiently as possible (Reigeluth, 1983). Students are given a set of "truths" to learn and apply. For example, a rule, such as Newton's first law is explicitly presented with a variety of supportive examples and activities. Students then practice using and applying the rule, and eventually are tested on their understanding. If mastery is achieved, students proceed to the next objective in the

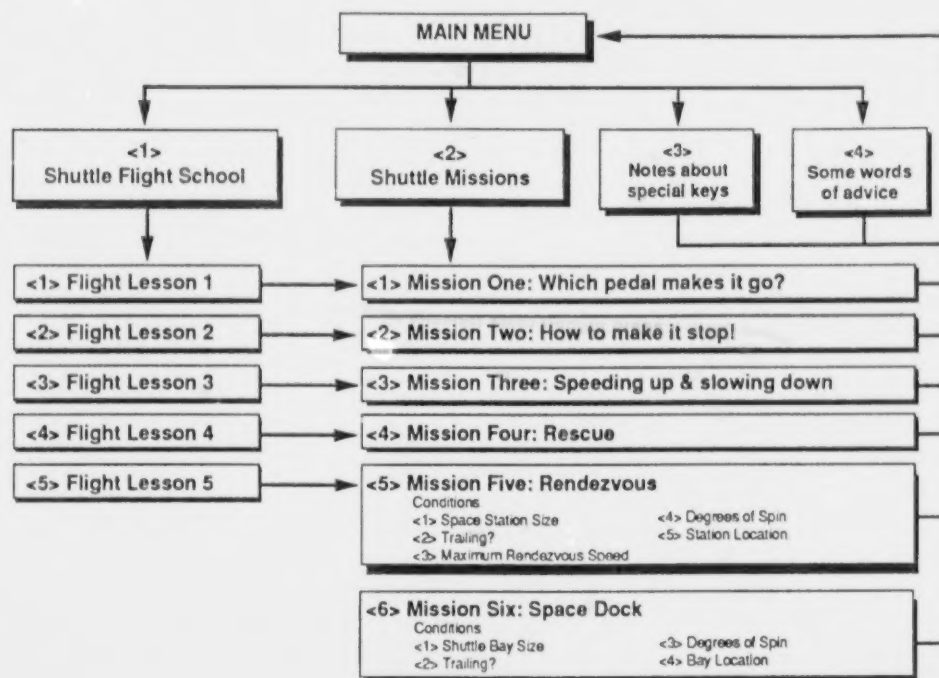
hierarchy; if mastery is not achieved, the students are either provided with remediation on the objective or are exited to receive instruction on prerequisites. In contrast, a constructivist approach involves largely inductive strategies where instances of a rule are provided with the goal that the learner will induce the rule for themselves. By so doing, learners make each "truth" they discover their own. The supposition is that this leads to deeper levels of understanding and also intrinsically motivates students to persist in the task.

The problems with extreme interpretations of either approach are obvious. Strict deductive approaches can lead to instructional designs which are unnecessarily self-limiting and which are inclined to assign a passive role to the learner. Instructional designs are likely to resemble one another resulting in activities which lack imagination and innovation. Deductive approaches are much easier to apply when learning outcomes involve verbal information because there is little need for interpretation or inference on the part of the learner. Conversely, strict inductive approaches resemble a "sink or swim" philosophy where learners may become either bored or frustrated if they are unable to generalize from the instances provided. In addition, novices often need structure or guidance which purely inductive experiences do not provide, a problem frequently encountered by designers of hypertext (Jonassen, 1986; Tripp & Roby, 1990). Inductive activities also require an attitude of playfulness and exploration which older children or adults may find as risky or threatening when being judged by peers.

In SSC, the activities are designed to follow either a deductive or inductive approach, as well as allowing the provision to switch between each approach. On the surface SSC is laid out essentially in a deductive fashion. The tutorials or "flight lessons" are hierarchically organized where later skills build on earlier ones, as Table 2 and the lesson flowchart in Figure 3 show. Each flight lesson "teaches" the respective objectives according to conventional instructional design and each "mission" acts as a suitable practice activity for each lesson (Gagné, Briggs, & Wager, 1988). Therefore, students can go through SSC in the classic deductive fashion, starting with the first Flight Lesson.

However, each mission acts as a stand-alone microworld which simulates one or more particular aspects of Newton's laws of motion as suggested by the lesson objectives shown in Table 2. For example, Missions 1, 2, and 3 take the learner through a series of activities which introduce the simplest aspects of Newton's first and second laws. At first, structure is heavily imposed, but then reduced as the learner establishes a foothold with these concepts. The first three

FIGURE 3. A lesson flowchart of Space Shuttle Commander.



missions further constrain the learner's experience to one dimension. Mission 4, as illustrated in Figure 4, introduces the effects of two dimensions in a highly structured way so as to make the simplest relationships of two-dimensional motion as explicit as possible. The artificial restraints on this microworld are presented in a "rescue" context where students are asked to imagine that their shuttle has been disabled by a collision with a meteorite. The collision has resulted in limited control of the shuttle.

It is possible, therefore, to have students begin to understand Newtonian mechanics by only having them explore the missions in SSC. The flight lessons become resources to provide formal accounts of the information or principles which students actually use on the missions. Flight lessons would be consulted only when clarification is needed, either the result of curiosity or confusion.

The most radical example of using an inductive approach with SSC would place students in one of the last two missions, such as "Rendezvous," depicted in Figure 1, or "Space Dock," depicted in Figure 5. Both are fully detailed simulations. Many students quickly become successful "commanders" of the space shuttle in these missions and usually seek to increase the challenge of the activities by changing the mission

conditions. Students who are not successful would be encouraged by on-line coaching (and hopefully by the teacher as well) to go through earlier missions or to consult the flight lessons.

In practice, most students choose a combination of deductive and inductive strategies. The teacher plays an important role to facilitate the best path for each student. A teacher who already has developed an established unit on Newton's laws might use SSC to supplement or supplant part of their curriculum. Other teachers might use SSC to fully guide students through the unit, but should feel free to explore other activities and ideas as well. SSC, like the original dynaturtle microworld, is designed to bring students in contact with ideas which conventional educational wisdom might suggest they are not ready for.

Emphasize the usefulness of errors. Errors are an inevitable part of the learning process without which learning would not occur. Inductive learning theories promote the ability of learners to detect errors and then incorporate the information learned in subsequent trials. Using errors in inductive learning is not meant to be a haphazard process, but is usually quite systematic. When confronted with the task of learning about two or more unknown variables, a learner must be able to isolate and manipulate each of the variables while

FIGURE 4. A representation of the computer screen during "Mission 4: Rescue." The goal of the mission is to maneuver a "disabled" shuttle to the space station. Students do not have control over the shuttle's rotation, and they only have enough fuel for three bursts of thrust. These constraints make the relationship of orthogonal forces more apparent. (Not drawn to scale.)

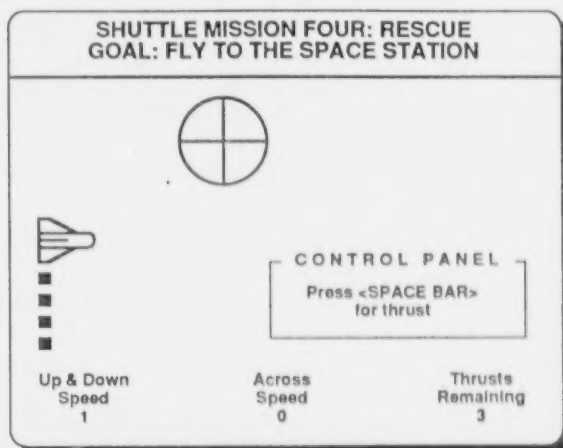
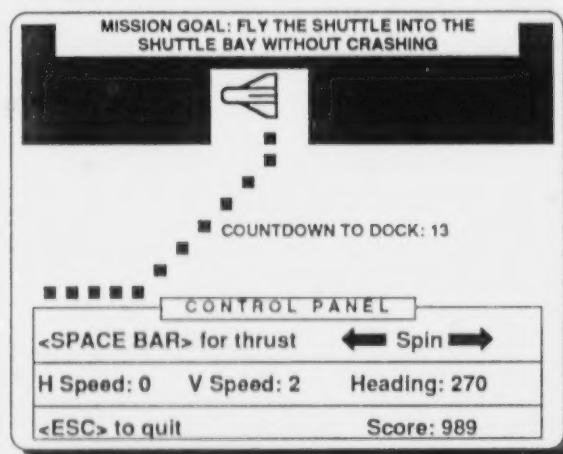


FIGURE 5. A representation of the computer screen during "Mission 5: Space Dock." The goal of this mission is to maneuver the shuttle into the shuttle "bay" of the space station without touching the walls of the bay or the station. (Not drawn to scale.)



holding all other variables constant. This systematic process of error handling forms the basis of hypothesis forming and testing, as shown in the research on concept formation (see Mayer, 1983, for a review). The ability of a learner to focus on one variable at a time while understanding the relationship among two or more variables is an example of decentered thinking (as compared to egocentric thinking), of which the ability to conserve is an example (Slavin, 1988).

Unfortunately, many learning tasks contain so many individual variables that a novice learner would soon be inundated with information, leading to frustration. Microworlds offer a way to structure a learning experience so that a finite set of variables are introduced at any one time. When these variables are mastered, additional variables can be introduced. Piaget called this *variable-stepping* which is an essential characteristic of forming and testing hypotheses. In classical mechanics, for example, problems can be simplified when presented in one rather than two

dimensions. In a computer microworld, like the SSC missions, this is accomplished in a number of ways. Certain computer commands can be activated or deactivated, depending on which variables are to be explored in a particular activity. Other commands can be constrained so as to produce a particular effect, such as limiting the rotation of the shuttle to 180 degree increments so that one-dimensional motion is produced.

Errors cannot be useful unless the goal of an activity is clearly known. If the goal is ambiguous, then all available feedback will also be ambiguous. In LOGO, for example, students often work towards the completion of a graphic which they have chosen, such as a house or a car. The graphical feedback they receive from the turtle is continually judged against their individually defined goals. In the best of cases, goal monitoring is automatic and intrinsic. The best rule of thumb for microworld design is to provide the simplest and clearest goals. An example of a mission goal in

SSC is "fly the shuttle to the space station."

Finally, a variety of secondary feedback features can also be used to complement primary feedback mechanisms. For example, the shuttle in SSC automatically leaves a trail in order to show the history of its travel path (although this feature can be turned off as many people find the trailing distracting at times). Verbal feedback can also be presented in tandem with visual feedback. SSC provides a "control panel" showing such information as the shuttle's vertical and horizontal speed and the shuttle's heading. Verbal feedback can be important when novices have difficulty seeing slight visual changes, such as when the shuttle is moving very slowly.

The importance of an attitude change toward errors on the part of teachers and students must be underscored. The negative connotation of errors is firmly rooted in school environments, and simply stating that errors should be considered useful will not change this. The attitude toward errors in learning is probably one of the starkest differences between behavioral and cognitive learning perspectives.

Anticipate and nurture incidental learning. Constructivist approaches accept the fact that learning does not necessarily flow from a fixed sequence of ideas. In LOGO programming, for example, mistakes or "bugs" often lead to other interesting phenomena and students often choose to abandon an original programming project in lieu of projects which follow unexpected results. However, this can make it difficult to identify and document mastery of learning goals. In contrast, instructivist approaches strive to take a group of learners through a sequence of predetermined learning objectives to the point of ignoring any learning which may be incidental to these objectives. Learners are not only less likely to explore a wider array of learning experiences, but are actually discouraged from doing so. Carefully designed microworlds should expect and encourage incidental learning to occur within design parameters. The teacher's role is again very important here. A teacher can help to channel incidental learning to serve the lesson or unit's terminal goals by helping to illustrate their relevancy. Likewise, students are apt to get sidetracked by incidental paths and a teacher should redirect a student back to relevancy if the incidental learning is too esoteric or counterproductive.

One example of the two edges of the incidental learning "sword" is provided by Rieber (in press) in which incidental learning from the tutorial sections of SSC was studied. Students in the study were given a tutorial on a simple application of Newton's second law where the acceleration of an object with a constant mass varies depending on the force that is applied to it.

However, students given an animated account of this principle also were taught another application of this physics law incidentally. Through animation, students saw the motion consequences when the same size force is applied to objects of different mass. Fourth grade students successfully extracted this incidental application even though no formal attempt was made to teach them the rule. However, these students continued to apply this incidental information to other *inappropriate* contexts, such as gravitation problems. The conclusion here is that students who learn in incidental ways apply this information in a variety of contexts: some of which may be appropriate and constructive to a larger set of learning goals; some of which may actually undermine some learning goals, such as by promoting misconceptions.

Closing

This paper has discussed the educational dilemma of promoting a constructivist philosophy within an educational system based on direct instructional methods. This is not necessarily the paradox it appears to be. Rather than being a destructive influence on instructional technology, it is contended that this tension is healthy and useful as well as necessary in the maturation of the field. This tension acts as a "dithering device" which motivates reflectivity and growth and helps to eliminate stagnation and professional nepotism. The ability to learn and otherwise progress in cognitive ways is a natural, innate and *personal* process for people and one which the constructivist approach advocates. Yet, most school instruction is often centered solely around the content and not the student. The instructivist approach sees learning as the mastery of a series of objectives where the mastery of one objective is seen as the starting point for the next. This approach risks the danger of focusing on the content to be learned, instead of the learner and the learning experience. Although the goals of education in terms of content are quite similar in each approach, the means to achieve those goals are radically different. It is suggested that computer microworlds offer an interesting compromise between the instructivist and constructivist approaches. Microworlds can be designed in such a way as to give users exploratory experiences within a carefully controlled range of concepts and principles and thereby offer a practical compromise between instructivism and constructivism.

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